PARSIMONIOUS DATA TRANSMISSION IN HAPTIC TELEPRESENCE SYSTEMS

P. Hinterseer, E. Steinbach, S. Hirche[1]*, M. Buss*[1]

Institute of Communication Networks, Media Technology Group
[1]Institute of Automatic Control Engineering
Technische Universität München, D-80290 Munich, Germany

ABSTRACT

Limited communication resources represent a major challenge in networked telepresence and teleaction systems. Video and audio compression schemes are well advanced employing models of human perception. In contrast to that haptic data reduction schemes are rather poorly treated in the known literature. This paper introduces a novel approach to reduce network traffic in haptic telepresence systems exploiting limits in human haptic perception. With the proposed deadband control approach data packets are transmitted only if the signal change exceeds a signal amplitude dependent perception threshold. Experimental user studies show that a network traffic reduction of up to 85 % can be achieved without impairing the perception of the remote environment. This study is performed under the assumption of a data transmission with zero communication delay.

1. INTRODUCTION

Advanced telepresence systems provide a human operator with sensory feedback adressing various modalities of human perception. Haptic feedback in addition to visual and auditory feedback provides the human operator with more complete information and increases the subjective feeling of presence in the remote environment thereby improving the ability to perform complex tasks [1]. The haptic feedback system as part of the multimodal telepresence system is visualized in Figure 1. It basically consists of three components: a force feedback capable human system interface (HSI), the remote robot (teleoperator) equipped with appropriate sensors, and a communication network for the transmission of the command signals from the HSI and the sensor information from the teleoperator.

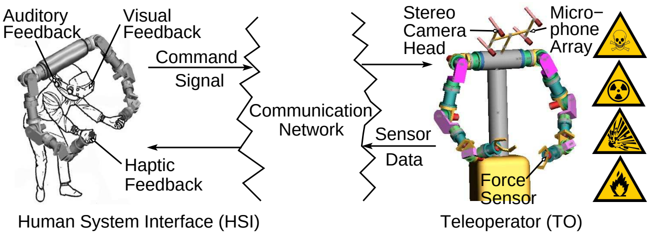

Fig. 1. Multimodal telepresence system.

The transmission resources of typical communication networks used in telepresence scenarios are limited. Severe communication constraints are imposed by the communication technology and infrastructure in space and underwater telepresence applications, see, e.g., [2] and references therein. Generally, in mobile (wireless) telepresence applications, higher network traffic is directly related to higher power consumption reducing the lifetime of the mobile agent. In common purpose communication networks, such as, e.g., the Internet, the limited communication resources are shared by multiple network applications. High network traffic may lead to network congestion and hence large transmission time delays and packet loss. Furthermore, for TCP-friendly flow control policies in IP (Internet Protocol) based networks, high packet rates are hard to maintain, see [3] and references therein. From this point of view it is of high interest to reduce the network traffic. Data compression methods as well as transmission protocols for digital video and audio are well developed. Perceptual models are successfully employed for the efficient compression of video and audio data; codecs such as MPEG-4 (video), MP3 (audio) and multimedia transmission protocols such as H.323 are standardized and commercialized. In contrast to that haptic data reduction techniques are rather poorly treated in the known literature.

One of the major challenges compared to standard coding applications is the stability requirement associated with the haptic control loop. Haptic interaction does not only provide the human operator with *information* about his/her environment, but enables the human operator to *manipulate* the environment. This implies a bilateral *exchange of energy* between human operator and environment. A closed control loop is formed by the HSI, the teleoperator and the communication network. Stability of this control loop is a fundamental property: an unstable system is inoperable, and furthermore imposes a severe hazard to the human operator and the environment. Accordingly, the design goal of haptic data reduction techniques is not only to achieve a realistic representation of

---

This work was supported in part by the German Research Foundation (DFG) within the Collaborative Research Centre SFB 453 on "High-Fidelity Telepresence and Teleaction".

the remote environment, i.e. transparency, but also to guarantee stability.

Only few researchers consider the compression of haptic data, mostly by applying quantization schemes [4–7]. Differential pulse code modulation (DPCM) is proposed in [6, 7], adaptive DPCM is considered in [4, 5]. Stability, however, is not discussed, nor are perceptual models employed. In packet-switched haptic telepresence systems the compression of haptic data has only a small influence on the network traffic load itself. In current telepresence systems the haptic command and sensor data are continously sampled in time at frequencies around 1000 Hz. Every single sample is transmitted in an individual data packet resulting in high data packet rates of approximately 1000 packets per second. As the haptic data load is comparably small, the protocol overhead accounts for the main portion of the network traffic volume (e.g. about 60 % with UDP[1]/IP and a six degree-of-freedom telepresence system). In order to reduce the network traffic the reduction of the packet rate is more efficient than the reduction of the haptic data load. Coarser quantization [4, 5, 7] implicitly allows a packet rate reduction, however, it is not considered in these works. In this paper the alternative approach of reducing the packet rate is pursued.

The main contribution of this paper is a novel control approach to significantly (up to 85 %) reduce the network traffic induced by haptic feedback systems without impairing the perception of the remote environment. In the proposed deadband control approach data are sent only if the difference between the current and the most recently sent value exceeds a perception threshold. Assuming a velocity-force architecture, the HSI velocity is communicated as command signal to the teleoperator, and the interaction force with the remote environment is fed back to the HSI. The deadband control is directly applied to velocity and force signals. A new force value is transmitted to the HSI only if the force amplitude has changed by the threshold value. Inspired by the well-known empirical laws of sensation and perception such as Weber's and Plateau-Brentano-Stevens law the absolute threshold is adapted to the magnitude of the signal to transmit, here force and velocity. In this paper exemplarily a deadband control strategy is investigated, where the threshold value linearly depends on the signal magnitude, i.e. corresponding to Weber's law. Experimental user studies are conducted with a one degree-of-freedom telepresence system to determine the deadband detection threshold. The network traffic is measured during the experiments. Our approach leads to a network traffic reduction of up to 85 % without impairing the perception of the remote environment.

The remainder of this paper is organized as follows: After an overview on existing approaches in Section 2, the deadband control principle is introduced in Section 3. The experimental user study is presented in Section 4.

2. STATE-OF-THE-ART

In a haptic telepresence system the human operator moves the HSI to command the motion of the teleoperator. The velocity of the HSI is measured in equidistant time intervals according to the sampling rate of the local velocity control loop. For stability and transparency reasons the local control loops operate at a rate of approximately 1000 Hz. The velocity is communicated to the remote site where local control loops ensure that the teleoperator follows the motion of the HSI. The teleoperator interacts with the remote environment and the environment force is communicated back to the HSI where local control loops ensure that the environment force is appropriately displayed to the human operator. A global control loop is closed over the communication network.

2.1. Network Traffic in Haptic Telepresence Systems

The current paradigm is to transmit *every* measurement, here velocity and force, in an individual data packet. The packet rate is equal to the sampling rate of the local control loops. This is visualized in Figure 2 where for an example signal the time instants of the measurements, i.e. the instants of sending a data packet, are represented by circles. Each data packet consists of the data to be transmitted and the packet header containing information such as, e.g., the destination address. In haptic telepresence systems the data load portion is generally rather small compared to the packet header as the following example illustrates.

Example: A haptic telepresence system with 6 degree-of-freedom (DoF) is considered with communication over a Internet protocol (IP) based network. The sampling rate is assumed to be 1000 Hz, hence the packet rate is 1000 packets/s. Corresponding to the number of DoF in each packet at least 6 values of type float (4 Bytes per value) are sent; the packet load is 24 Bytes . Using RTP/UDP/IP[2] as the protocol for the transmission the protocol header is 40 Bytes (12 Bytes for RTP, 8 Bytes for UDP, 20 Bytes for IPv4), see e.g. [8] for reference. The traffic volume per packet is 64 Bytes. The minimal required communication bandwidth is 500 kBit/s for the forward as well as for the backward communication path.

In haptic telepresence systems, even though the packet load itself is low, the communication rate requirement is comparable to compressed streaming video as the packet rate is very high. As discussed in Section 1, severe communication constraints are imposed in typical telepresence scenarios and hence efficient network traffic reduction techniques are highly desirable.

2.2. State-of-the-Art Data Reduction Methods

Data compression methods as well as transmission protocols for digital video and audio are well developed. Perceptual

---

[1] UDP - User Datagram Protocol

[2] RTP - Real-time Transport Protocol

models are successfully employed for the efficient compression of video and audio data; codecs such as MPEG-4 (video), MP3 (audio) and multimedia transmission protocols such as H.323 have been standardized and commercialized. In contrast to that haptic data reduction techniques are rather poorly treated in the known literature. The encoding and decoding takes place in a closed control loop, hence stability with data reduction is a major issue. For example, time delay introduced by encoding or decoding may destabilize the closed loop system.

Only few researchers considered the compression of haptic data. In [4–7] quantization is employed, i.e. the resolution of the signal value is reduced. Differential pulse code modulation (DPCM) together with a fixed rate quantization has been proposed in [7], DPCM with Huffman coding in [6], and adaptive DPCM together with Huffman coding has been considered in [5]. In DPCM local predictions for the signal development are performed at the sender as well as on the receiver side, the prediction error is quantized and transmitted. As the prediction error is smaller in magnitude than the signal itself fewer quantization steps are necessary to achieve the same quantization noise level as with straight signal quantization. In the adaptive DPCM scheme the quantization is temporarily adapted to phases of, e.g., fast and slow motion. Alternatively to quantization, the reduction of sampling rate is a means to compress data. The lossless compression scheme proposed in [4] adapts the sampling rate to the highest signal frequency occuring over a past window. A large window size results in high compression rate, however, also in high time delay introduced by this scheme and is therefore not appropriate for networked telepresence systems.

With the protocol overhead being the dominant component of the haptic telepresence systems induced network traffic volume (62.5 % in the above example), reducing the size of the packet payload, e.g., by coarser quantization, has only little effect on the network traffic volume. Reducing the number of transmitted packets on the other hand, significantly reduces the traffic volume. The quantization based approaches [5, 7] implicitly allow for packet rate reduction: The signal to transmit takes fewer discrete values, subsequent equal values do not have to be transmitted if a Hold-Last-Sample strategy is employed on the receiver side. This, however, is not considered there. Following the sampling/packet rate reduction paradigm in this paper a deadband control approach is introduced. Haptic perception is explicitely considered, and stability is investigated. The basic principle is explained in the following.

3. DEADBAND CONTROL PRINCIPLE

With deadband control measurements are sent over the communication network only if the difference between the current measurement and the most recently sent value exceeds a certain threshold, the deadband width. As a result data packets are no longer transmitted in equidistant time intervals. This is visualized in Figure 2 where the time instants of packet transmission for the example signal when using our deadband approach are represented by triangles. Deadband control obviously leads to a reduction of the number of transmitted packets: If, for example, the teleoperator moves in free space motion (zero force) then no force data packets at all are transmitted. Accordingly, if the HSI does not move or moves with a constant velocity, no velocity packet is transmitted, either.

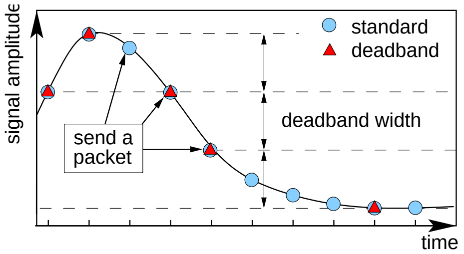

Fig. 2. Visualization of the deadband control approach in comparison with the standard approach.

The deadband approach to reduce network traffic can be interpreted as a lossy compression algorithm exploiting the fact that the human is not able to discriminate arbitrarily small differences in haptic stimuli, see e.g. [9, 10]. For most force-related physical quantities the ratio of the discrimination threshold over the base level input is roughly constant over a large range [9] and can therefore be represented by Weber's law [11]. The discrimination threshold, called *just noticable difference* (JND), for force perception with hand and arm is around 10% [9], for velocity around 8% [10]. Inspired by these results a relative deadband is considered here, where the absolute deadband width Δ grows proportionally with the magnitude of the most recently transmitted value $x(t')$ representing either the HSI velocity or the teleoperator force

$$\Delta(t) = \Delta_{s(t')} = \epsilon|s(t')|, \tag{1}$$

the proportional factor ϵ represents the relative deadband parameter, t is the current time, and t' is the time instant of the most recent transmission. If the measurement is close to zero then the absolute deadband width Δ becomes very small, theoretically it may become infinitely small resulting in high packet rate. For this reason a lower bound Δ_{min} is introduced, which in practical application can be tuned such that the number of transmitted packets is insensitive to measurement noise.

3.1. Stability Issues

The transmission of fewer data packets itself does not have an effect on the stability of the haptic feedback system. However, at each receiver side the local control loops still operate at the original constant sampling rate. Accordingly, updates of the current velocity/force measurement are required in each sampling instant. Due to the deadband control, however, these measurements are not directly available at each sampling time instant, but only if a data packet is transmitted. The missing measurements, namely the desired teleoperator velocity $\dot{x}_t^d$ and the desired HSI force f_h^d, have to be reconstructed. As this takes place in the closed control loop, the data reconstruction has to preserve stability. The data reconstruction algorithm

$$\begin{aligned} f_h^d(t) &= f_e(t') + \text{sign}\{\dot{x}_h(t)\} \cdot \Delta_{f_e(t')} \\ \dot{x}_t^d(t) &= \dot{x}_h(t') - \text{sign}\{f_e(t)\} \cdot \Delta_{\dot{x}_h(t')}, \end{aligned} \tag{2}$$

with f_e the environment force, $\dot{x}_h$ the HSI velocity, and the signum function

$$\text{sign}\{x\} = \begin{cases} -1 & \text{if } x < 0 \\ 1 & \text{otherwise,} \end{cases}$$

guarantees stability of the closed loop system. The first term corresponds to a Hold-Last-Sample, which is widely used in sampled data systems. It is modified by the latter term such that no energy is generated, i.e. stability is guaranteed. For further details including a stability proof please refer to [12]. The overall system architecture including the deadband control and the data reconstruction is presented in Figure 3.

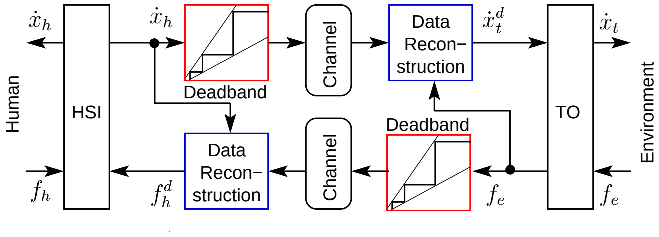

Fig. 3. System architecure with deadband control.

3.2. Transparent Design

A haptic telepresence system is called transparent if the human operator may not distinguish between direct and tele-interaction. Ideally he/she feels direct interaction with the remote environment [13]. Here a weaker interpretation is employed: A haptic data reduction scheme is called transparent if the human operator may not distinguish between haptic tele-interaction with and without haptic data reduction.

The level of transparency with the deadband approach is determined by the size of the deadband parameter ϵ (1). A low value results in low distortion of the velocity and force signals. On the other hand, a significant packet rate redcution is achieved only for appropriate values of the deadband parameter. However, considering the limits of human haptic perception the haptic data reduction may still be transparent with slightly distorted signals. Thus, the design goal is to minimize the network traffic by maximizing the deadband parameter while maintaining transparency. Therefore, detection thresholds are determined in an experimental user study in the next section.

The distortion of the velocity signal does not only effect the perception of the velocity itself, the velocity error between the HSI and the teleoperator may also lead to a position drift between the HSI and the teleoperator. The position drift does not only deteriorate the transparency, but may also drive the system to inoperability if the HSI or the teleoperator reaches the limit of its workspace. In [14] the velocity/force architecture is extended by a position feedforward. In order to improve the position tracking this architecture is applied here. A HSI position update is transmitted together with the HSI velocity and used for the teleoperator control.

4. EXPERIMENTAL USER STUDY

Our design goal is to minimize the network traffic while maintaining transparency as indicated in the previous section. For this we determine the maximum value of the deadband parameter ϵ where the system still appears transparent. In the following experimental user study the detection threshold ϵ is determined. Furthermore, the effect of the deadband parameter ϵ on the network traffic is studied.

4.1. Experimental Apparatus and Conditions

The experimental setup consists of two identical 1-DOF haptic devices connected to a PC and a stiff wall as the environment as shown in Figure 4. The teleoperator can be moved in free space and a stiff wall (wooden plank) can be touched. The angle of the devices is measured by an incremental encoder, the force by a strain gauge. The sensor data are processed in the PC where all control algorithms (HSI force control, teleoperator velocity control) including the deadband control (1) and the data reconstruction (2) are implemented. The control loops operate at a sampling rate of 1000Hz representing the standard packet rate without deadband control. The deadband control and the data reconstruction strategy are equally applied with the same deadband parameter value for the velocity and force signal, i.e. in the forward and the backward path. The lower bound, see Section 3 is set to a small value of $\Delta_{\dot{x},\text{min}} = 0.001\,\text{rad/s}$ for the velocity and to $\Delta_{f,\text{min}} = 0.02\,\text{N}$ for the force, chosen such that measurement noise has no influence.

4.2. Procedure

Altogether 14 subjects (3 female, 11 male, aged 20–50) were tested for their detection threshold of the deadband parameter ϵ. Only three of the subjects had an idea what the distortion the deadband parameter introduces in the system would feel like. Those three had also prior contact with the experimental setup. The other 11 subjects did not know what to expect.

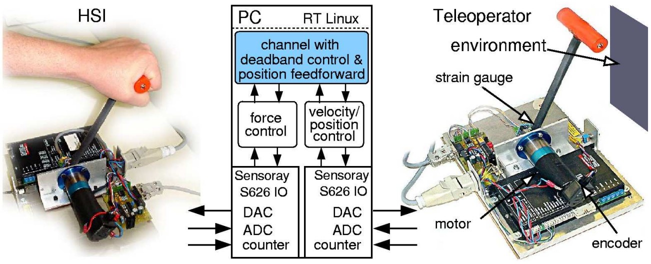

Fig. 4. Experimental apparatus: A one degree-of-freedom haptic telepresence system.

None of the subjects had any impairments of sensorimotor capabilities. The subjects were not reimbursed.

The subjects were told to operate with their preferred hand. They were equipped with earphones to mask the sound the device motors generate. The view to the teleoperator device was blocked so no information could be drawn from the teleoperator behavior. During a familiarization phase subjects were told to feel operation in free space and in contact with a stiff wall without deadband control applied. As soon as they felt familiar with the system the measurement phase began.

The deadband parameter detection thresholds were determined using a three interval forced choice (3IFC) paradigm. The subjects were presented with three consecutive 20s intervals in which they should operate the system. Only in one of the three intervals, which was randomly determined, the deadband algorithm with a certain value ϵ was applied. The other two were without deadband control. Every three intervals the subject had to tell which of the intervals felt different than the other two. The experiment started with a deadband parameter $\epsilon = 2.5\%$ and was increased after every incorrect answer up to a maximum of 25%. When an answer was correct, the same value was used again until three consecutive right answers were given. After this first pass, the subjects were told how the distortion feels like and with what kind of technique they should be able to perceive it best. Then the same procedure as before was applied. After another three consecutive right answers ϵ was reduced by 50% without telling the subjects and the procedure was repeated. The mean value of the three ϵ values at which the consecutive right answers occurred were taken as the deadband detection threshold for the specific subject.

4.3. Experimental Results

The specific results for every subject are shown in Figure 5. Comparing the results of the three passes for the individual subject, all subjects had a significantly higher detection threshold in the first pass when they did not know what kind of distortion they had to expect. Hence, the distortion introduced by this deadband approach is not necessarily perceived as disturbing or impairing the contact impression. The subject specific detection thresholds are in the range between 10% and 22.5%. Only one subject managed to detect the distortion introduced by $\epsilon = 10\%$, for the remaining 13 subjects corresponding to 93 % a higher threshold was determined. Eleven subjects (79 %) had a detection threshold $\epsilon > 11\%$. The detection thresholds are at least in the range of the JND's for velocity and force perception [9, 10]. It should be noted, however, that JND's are typically determined in static conditions. Here a temporal change of the signal is considered. The relation between JND's and the deadband results needs further investigation.

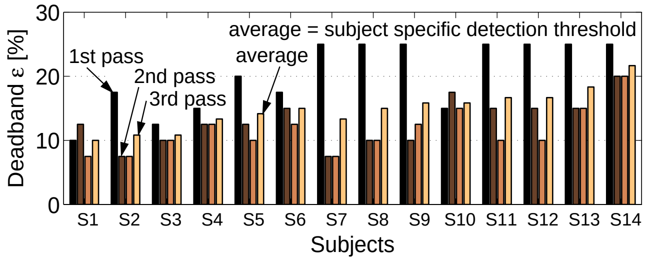

Fig. 5. Results of our subjective experiment for 14 test subjects.

In order to investigate the effect of the deadband control the induced network traffic was recorded during the experimental user study. The mean percentage of transmitted packets as a function of the deadband parameter ϵ is shown in Figure 6; 100 % represent the standard approach with 1000 packets/s on the forward and the backward path, respectively. As expected, higher deadband parameter leads to higher traffic reduction. The traffic volume induced by velocity packets is already at 25 % at a deadband size of $\epsilon = 10\%$ and keeps falling with increasing deadband size. The impact on the number of force packets transmitted is even higher. Already at $\epsilon = 2.5\%$ the network traffic volume in the backward path is less than 10 % of the standard approach. At $\epsilon = 10\%$ only 15 % of the original number of packets is transmitted. This means an average network traffic reduction by 85 %; 93% of the subjects were not able to feel the transparency deterioration introduced by the corresponding deadband parameter.

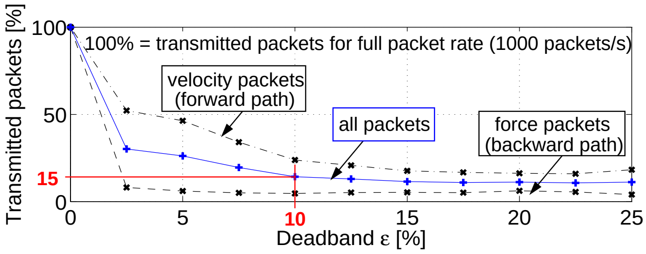

Fig. 6. Network traffic reduction by deadband control: Average number of transmitted packets depending on the deadband parameter ϵ.

In summary, the deadband control approach is very promising with respect to transparent network traffic reduction in haptic telepresence systems. It should be emphasized, however, that the reported network traffic reduction is a mean value. Strict communication rate guarantees cannot be given.

5. CONCLUSIONS AND FUTURE RESEARCH

The main contribution of this paper is a novel approach to reduce the network traffic in haptic telepresence systems. The proposed deadband control transmits a haptic data packet only if the difference between the current and most recently sent value exceeds a certain threshold. Inspired by Weber's law the threshold proportionally increases with the signal magnitude. As zero time delay is assumed here for the data transmission, the deadband is directly applied to velocity and force signals. Stability is guaranteed by appropriate data reconstruction. The deadband detection threshold of 14 subjects is determined in an experimental user study with a one-degree-of-freedom telepresence system. The results show that a significant network traffic reduction of up to 85% is achieved without impairing the perception of the remote environment. The presented algorithm is to the authors knowledge the first approach exploiting human haptic perception to reduce the data rate of haptic information.

Future research is to determine the optimal deadband strategy, its combination with prediction as in DPCM and the extension of the approach to multi-degree-of-freedom systems. A long term goal is the definition of haptic data reduction standards and protocols and an integrated approach to data transmission in multimodal networked telepresence and teleaction systems.

6. REFERENCES

[1] T.B. Sheridan, *Telerobotics, Automation, and Human Supervisory Control*, MIT Press, Cambridge, Massachusetts, 1992.

[2] I.F. Akyildiz, D. Pompili, and T. Melodia, "Challenges for Efficient Communication in Underwater Acoustic Sensor Networks," *ACM SIGBED Review*, vol. 1, no. 2, 2004.

[3] C. Mahlo, C. Hoene, A. Rosami, and A. Wolisz, "Adaptive Coding and Packet Rates for TCP-Friendly VoIP Flows," in *Proceedings of 3rd International Symposium on Telecommunications IST2005*, Shiraz, Iran, 2005.

[4] C. Shahabi, A. Ortega, and M. R. Kolahdouzan, "A Comparison of Different Haptic Compression Techniques," in *Proceedings of the International Conference on Multimedia and Expo (ICME)*, Lausanne, Switzerland, 2002, pp. 657–660.

[5] A. Ortega and Y. Liu, "Lossy Compression of Haptic Data," in *Touch in Virtual Environments: Haptics and the Design of Interactive Systems*, G. Sukhatme M. McLaughlin, J. Hespanha, Ed., pp. 119–136. Prentice Hall, 2002.

[6] A. Kron, G. Schmidt, B. Petzold, M. F. Zäh, P. Hinterseer, and E. Steinbach, "Disposal of Explosive Ordnances by Use of a Bimanual Haptic Telepresence System," in *Proceedings of the IEEE International Conference on Robotics and Automation*, New Orleans, USA, April 2004, pp. 1968–1973.

[7] C. W. Borst, "Predictive Coding for Efficient Host-Device Communication in a Pneumatic Force-Feedback Display," in *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Pisa, Italy, 2005, pp. 596–599.

[8] J. F. Kurose and K. W. Ross, *Computer Networking: A Top-Down Approach Featuring the Internet*, Addison-Wesley, Boston, MA, US, 2003.

[9] G.C. Burdea, *Force and Touch Feedback for Virtual Reality*, John Wiley, 1996.

[10] L. A. Jones and I. W. Hunter, "Human Operator Perception of Mechanical Variables and Their Effects on Tracking Performance," *ASME Advances in Robotics*, vol. 42, pp. 49–53, 1992.

[11] E. H. Weber, *Die Lehre vom Tastsinn und Gemeingefühl, auf Versuche gegründet*, Vieweg, Braunschweig, 1851.

[12] S. Hirche, *Haptic Telepresence in Packet Switched Communication Networks*, Ph.D. thesis, Technische Universität München, Institute of Automatic Control Engineering, July 2005, http://www.mediatum.ub.tum.de.

[13] G.J. Raju, G.C. Verghese, and T.B. Sheridan, "Design Issues in 2-Port Network Models of Bilateral Remote Teleoperation," in *Proceedings of the IEEE International Conference on Robotics and Automation*, Scottsdale (AZ), US, 1989, pp. 1317–1321.

[14] N. Chopra, M.W. Spong, S. Hirche, and M. Buss, "Bilateral Teleoperation over Internet: the Time Varying Delay Problem," in *Proceedings of the American Control Conference*, Denver (CO), US, 2003, pp. 155–160.